ECONOMIC RADIOISOTOPE THERMOELECTRIC GENERATOR STUDY PROGRAM

COST EFFECTIVENESS STUDY
NOVEMBER 1973

MASTER

Prepared for Space Nuclear Systems Division, U. S. Atomic Energy Commission, Germantown, Maryland
AEC Contract SNSO-3

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TELEDYNE ISOTOPEs

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FOREWORD

This document was prepared for the United States Atomic Energy Commission, Space Nuclear Systems Division, by the Energy Systems Division of Teledyne Isotopes under Contract SNSO-3. This is Volume IV, Cost Effectiveness Study. Volume I is the Final Technical Report. Volume II is the Appendices for the Final Report, and Volume III is the Program Plan.

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ERTG COST EFFECTIVENESS STUDY

I. INTRODUCTION AND OBJECTIVES

During the conceptual and early design phases for an RTG program, the status of various technologies, weight, configuration envelope restrictions, and power requirements are just a few of the many factors that strongly influence the design. Probably for the first time in the evolution of radioisotope thermoelectric generators, program costs have been formally introduced as a significant influence on RTG design. The recently completed ERTG study and its resulting design definition were greatly dependent on a parallel cost effectiveness study and the results of numerous cost trade-offs. Both the total program activity and the ERTG design have been cost optimized.

Figure I-1 illustrates the approach taken in this cost effectiveness study for the ERTG in the form of a flow chart where the cost is subdivided into two categories. These are the constant or fixed costs and variable costs. The constant costs include manpower and direct charges that are independent of the selected generator design. For example, the required manpower allocated for administration (program management, planning, finance, and contracts) is somewhat dependent upon the duration of the total program, but is rather independent on the design. This is not to say that the estimates for the constant costs are automatic. A considerable effort has been made to minimize these costs. A good example is the planned series of safety qualification tests. Test facilities and test techniques have been chosen which reflect minimal cost without compromising either qualification integrity or technical value.

The variable costs relate to the many trade-off studies that have been conducted, which include value determination of developmental efforts versus a more

FIGURE I-1. ERTG COST EFFECTIVENESS PROGRAM

state-of-the-art technical approach. A question is asked whether or not the cost is worth the gain in versatility or efficiency, etc., to the RTG system. The trade-off studies conducted were designed to answer this and similar questions.

The resulting study of the constant and variable costs along with price estimates for heat pipes (Dynatherm), thermoelectrics (3M), and fuel capsule fabrication and assembly (ORNL) provides the basis for the total cost of 10 and 20 RTG's.

Although the radiation levels of ^{244}Cm are substantially higher than ^{238}Pu , the potential cost savings from the use of the former in fueling RTG's is significant. Curium in the form of curium sesquioxide, with its half life of about 18.1 years, is the best choice for the ERTG heat source due to its high melting point, low vapor pressure and good thermal stability characteristics. Its compatibility with potential capsule materials is presently under study at ORNL.

From reference 1 it is reported that within the next decade the potential recovery cost of ^{244}Cm could be between \$11 and \$100 per thermal watt, depending upon the recovery process options chosen for reprocessed reactor wastes and the volume of yield required.

The useful form of hot pressed pellets of Cm_2O_3 requires an additional fabrication cost estimated at \$42 and \$28 per thermal watt on a 10 kg/year and 20 kg/year production level, respectively.

In this study, a nominal cost of \$100 per thermal watt (Reference 2) at the time of encapsulation was used as the cost of the pressed and sintered Cm_2O_3 fuel pellets. The cost effectiveness trade-off studies also incorporate the influence of fuel cost variability with \$50 and \$150 per thermal watt as lower and upper bounds, respectively. Plutonium dioxide at \$600 per thermal watt in the pressed and sintered pellet form ready for encapsulation has also been evaluated for the ERTG design. This value is based upon present costs which could conceivably be somewhat reduced over the next few years.

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II. ERTG PROGRAM COSTS

A. ERTG DESIGN DEFINITION

Figures II-1 and II-2 provide pictorial views of the ERTG and heat source assembly, respectively. Table II-1 presents the more significant system design data associated with the ERTG.

B. PROGRAM SCHEDULE AND COST ESTIMATES

The cost estimate for the development and production ERTG program is partially dependent upon the schedule presented in Figure II-3, where the total program is subdivided into phases. The phases are defined per the suggested guidance for preparation of the development plan and cost estimates of Reference 3. A brief definition of the program phases is as follows:

Phase II	Technology and/or Component Demonstration
Phase III	System Development and Qualification - includes fabrication and test initiation for two (2) ETG's and a prototype RTG.
Phase IV	Flight System Fabrication - delivery of two (2) flight qualified RTG's.
Phase V	Follow-on Production - fabrication and delivery of ten (10) flight qualified RTG's.
Phase V-A	Follow-on Production - an extension of Phase V with the delivery of an additional ten (10) RTG's.

Program costs presented in the following pages are given both as a function of the phases and by fiscal year. Detailed cost estimates for the major government agency and subcontracted development and production hardware including Dynatherm (heat pipes), 3M (thermoelectrics) and ORNL (heat sources) are presented in the Appendices of this report.

FIGURE II-1. ERTG REFERENCE DESIGN

FIGURE II-2. MODULAR HEAT SOURCE ASSEMBLY

TABLE II-1
ERTG DESIGN DATA

Heat Source Dimensions (inches	2 x 3 x 3.7 (Cm); 2 x 4 x 3.7 (Pu)
BOL Radiator Temperature (°F)	300
Diameter and Height (inches)	36 x 60
Weight with Curium (pounds)	104
BOL Thermal Inventory (watts)	4663
Specific Power (watts/pound)	3.85
η_{TH} (%) at BOL	88.1
$\eta_{T/E}$ (%) at BOL	12.65
η_{System} (%) at BOL	11.14
T/E Area (sq. inch)	75.4
Number of T/E Couples	660
Number of Heat Pipes	40
Diameter of Heat Pipes (inches)	0.375
Output Power (watts(e)) at BOL	519
Output Power (watts(e)) at EOM	400
Current at BOL (amps)	17.3
Current at EOM (amps)	13.3
Load Voltage (vdc)	30

The direct labor costs presented were estimated with the following considerations:

1. Average rates were developed from an employee-mix of present actual rates and weighted according to the degree of anticipated participation. These rates are escalated for each fiscal year based upon salary review projections as reviewed by management for the duration of the program.
2. Hours are estimated on a combination of work-event related and work-time related bases. For the majority of estimates, an average conversion factor of 156 man-hours per basic work month was employed.

Computer costs are based upon the present rate of \$910 per hour (Control Data Corporation 660 system at Westinghouse, Pittsburgh) plus \$2450 per month for terminal, phones and upgrading. Supply costs are estimated at \$32 per hour of computer time.

The overhead burden rates used in this estimate are presented in Table II-2 by GFY. These rates are derived from current experience and prospective projections over the term of this program. The general and administrative expense (G & A) rates applied are also presented in Table II-2.

TABLE II-2PROJECTED OVERHEAD AND G&A EXPENSE(In Percent)

GFY	74	75	76	77	78	79	80	81	82
Overhead	142.3	139	127	135	137	138	139	138	138
G&A	23.3	19	18	18.5	19	19	19	19	19

The following tables present the detailed manpower requirements and program costs.

Table II-3. ERTG Manpower - Direct Labor by Fiscal Year for ERTG Development

Table II-4. Teledyne Capital Equipment and Associated Direct Labor

Table II-5. ERTG Material Costs

Table II-6. Other Direct Costs

Table II-7. Subcontract Costs (Development)

Table II-8. Other Participating Organizations

Table II-9. Summary of ERTG Development Program Costs

Table II-10. Cost per ERTG

Figure II-3 illustrates the Teledyne Isotopes manpower distribution by phase and government fiscal year.

TABLE II-3
ERTG MANPOWER
DIRECT LABOR BY FISCAL YEAR FOR ERTG DEVELOPMENT

GFY:	74		75		76		77		78		totals	
	MM	K\$	MM	K\$	MM	K\$	MM	K\$	MM	K\$	MM	K\$
Task I - Program Management & Administration	15.0	26.05	36.0	63.95	84.0	138.75	75.0	130.64	49.5	91.02	259.5	450.41
Task II - System Design & Development												
Design	28.3	30.80	74.4	80.59	64.7	76.18	55.5	68.89	34.2	44.50	257.1	300.96
Material Tech. & Comp. Demo.	7.9	12.60	31.2	50.58	57.0	84.44	51.5	80.21	34.8	56.79	182.4	284.62
Hi Temp. Heat Source Study	5.0	8.95	37.2	68.07	15.1	29.02					57.3	106.04
Planning	5.0	6.44	12.0	15.87	12.0	16.66	6.0	8.75			35.0	47.72
Mass Model									8.4	10.74	8.4	10.74
Task III - Manufacturing, Fabrication & Q.C.												
Planning	5.0	6.44	12.0	15.87	12.0	16.66	12.0	17.50	9.0	13.79	50.0	70.26
Test Heat Sources	3.7	3.39	9.2	8.72	10.2	10.14	5.4	5.65			28.5	37.9
ETG, RTG Manufacturing	9.1	8.36	22.0	20.83	104.8	104.31	98.8	103.30	69.7	76.44	304.4	313.24
GSE Manufacturing					12.6	12.56	12.6	13.19	9.4	10.33	34.6	36.08
Task IV - Systems Analysis & Test												
Analysis	30.5	45.31	106.0	163.90	100.5	162.87	70.5	122.87	45.0	82.14	352.5	577.09
Generator Testing			30.2	37.96	73.5	45.88	61.7	85.29	38.4	56.46	203.8	275.59
Component Testing	24.0	30.33	56.4	72.46	52.8	70.22	33.2	45.46	9.0	11.67	175.4	230.14
T/E Testing			16.7	18.57	22.0	25.66	16.2	21.12	6.9	10.90	61.8	76.25
Post Flight Analysis									4.5	8.39	4.5	8.39
Task V - Safety & Reliability												
Reliability	5.0	6.60	26.7	34.72	38.7	50.02	32.9	44.92	19.7	28.60	123.0	164.86
Safety Analysis	22.1	38.65	52.9	94.54	36.0	64.80	31.4	59.91	20.6	41.67	163.0	299.57
Safety Testing	8.9	8.49	21.0	20.41	62.4	61.71	37.2	36.07	9.0	5.78	138.5	132.46
Task VI - GSE Design					28.8	37.39	13.1	17.12	1.8	3.36	43.7	57.87
Task VII - Quality Engineering	6.5	8.92	15.6	21.97	37.2	49.06	37.2	51.53	30.1	43.51	126.6	174.99
TOTALS	176.0	241.33	559.5	789.01	824.3	1106.33	650.2	912.42	400.0	596.09	2610.0	3645.18

FIGURE II-4. ERTG MAN POWER ALLOCATION BY PHASE AND FISCAL YEAR

TABLE II-4
TELEDYNE CAPITAL EQUIPMENT

<u>Nomenclature</u>	<u>Cost (\$)</u>
Vacuum Equipment	8,000
Test Lab Equipment	
Vertical TV Chamber	200,000
50 KW Emergency Generator	7,000
Module Tester (5)	100,000
RTG Test Station (4)	20,000
Digital Thermometer (6)	5,400
Digital Multimeter (6)	12,000
RGA	15,000
LN ₂ Line	2,000
2 Ton Crain	2,000
Manufacturing Equipment	
Electron Beam Welder	200,000
10-12 Ton Press	50,000
Outgas Station	3,000
Bonding Furnace	1,500
Large Bed Milling Machine Mod.	2,000
Grit Blast Cabin	500
Plating & Cleaning Tanks	8,500
Spray Booth	4,000
Bonding Oven	12,000
Fixtures & Hardware	50,000
Development Equipment	
Ultrasonic Soldering Iron	1,800
Plating Tanks	2,000
Cleaning Tanks	500
Trace O ₂ Analyzer	1,200
Trace H ₂ O Analyzer	1,500
Digital Thermometer (2)	1,600
Strip Chart Recorder	2,000
Plasma Spray Chamber	1,000
Plasma Spray Gun	6,000
Inert Gas Furnace	5,000
Vacuum Braze Furnace	800
Vacuum Retorts	2,000
Leak Test Stand	1,000
Acoustic Emittance Test	15,000
Dri-Train	7,000
Hi Vac Plumbing	800
TOTAL	752,100

TABLE II-4 (Continued)CAPITAL EQUIPMENT DIRECT LABOR

(Cost by Fiscal Year)

	GFY 75	76	77
Manufacturing	60,000	79,500	20,000
Facilities	17,470	18,350	9,630
Total	77,470	97,850	29,630

TABLE II-5
ERTG MATERIAL COSTS
 (By Phase and Fiscal Year)

TASK II	Cost in Dollars								
	Phase:	<u>II</u>	<u>III</u>	<u>IV</u>	<u>V</u>	<u>V-A</u>			
Pt-3008				21,400	107,000	107,000			
Heat Source Material		19,100	30,600	23,100	163,700	163,700			
Material Design Service		20,000							
Welding Consultant		4,000	10,000						
Weld & Seal Development		14,500							
Vent Material		2,500							
Coating Tests		2,700							
Capsule Development Material		25,000							
Cleaning Material		3,000							
Coating Material		400							
Bimetallic Seal		800							
Isolation Can		600							
Electrical Heat Source		1,200							
Electrical Receptacle		500							
Heat Source Supports		900							
Insulation Tests		1,200							
Heat Pipe Bond		20,000							
Bellows		1,000							
Heat Source Channel Space		400							
Hi Temperature Insulation		2,000							
Fuel Port Closure		2,000							
Burst Disc		900							
Vents		1,000							
Hydraulic Diaphragm		800							
Heat Pipe Qual. Fin		100							
Instruments		25,000							
Electrical Heaters			(3) 8,250	(2) 5,500	(10) 27,500	(10) 27,500			
Heater Tooling			4,000						
Misc. Material and Test			26,500	10,000		3,000			
Mass Model Material			1,500						
Totals		149,600	80,850	70,000	301,200	301,200			
Totals by Fiscal	<u>74</u>	<u>75</u>	<u>76</u>	<u>77</u>	<u>78</u>	<u>79</u>	<u>80</u>	<u>81</u>	<u>82</u>
Year in K\$	44	105.6	53.9	54.95	85.03	172.11	172.11	172.11	43.03

TABLE II-5 (Continued)
ERTG MATERIAL COSTS
 (By Phase and Fiscal Year)

<u>TASK III</u>	Cost in Dollars								
Phase:	<u>II</u>	<u>III</u>	<u>IV</u>	<u>V</u>	<u>V-A</u>				
Aluminum Housing Material	900	3,230	2,000	8,400	8,400				
Isolation Can - Haynes	500	3,000	1,700	7,200	7,200				
Bellows	660	1,000	650	2,600	2,600				
Marman Clamps	800	1,600	1,200	4,800	4,800				
Bimetallic Joint Materials	500	750	500	2,500	2,500				
Min-K Plate	440	3,600	2,400	11,200	11,200				
T/C Wire	100	600	400	1,900	1,900				
Miscellaneous Connectors	20	60	40	400	400				
Solder and Chemicals	30	150	110	600	600				
Outgassing Valve	600	600							
Electrical Connector	375	1,000	625	2,875	2,875				
Pressure Transducer	5,400	7,200	3,600	18,000	18,000				
RTD	5,250	8,250	4,500	22,500	22,500				
Thermistor	1,050	1,360	825	3,700	3,700				
Insulation Jackets	600	2,100	1,400	7,000	7,000				
Miscellaneous Material	80	120	80	400	400				
Parts Handling	100	500		500	500				
Shipping Container Material	300	1,650	1,100	5,500	5,500				
Tooling	1,800	4,100		600	600				
Q.C. Tools	6,500	5,000	4,000	7,000	7,000				
Neutron Shield Material		450	450	4,500	4,500				
Heat Pipes (Dynatherm)	6,256	46,920	31,280	156,400	156,400				
<hr/>									
Totals	32,261	93,240	56,860	268,575	268,575				
<hr/>									
	<u>74</u>	<u>75</u>	<u>76</u>	<u>77</u>	<u>78</u>	<u>79</u>	<u>80</u>	<u>81</u>	<u>82</u>
Totals by Fiscal									
Year in K\$	9.49	22.77	62.16	53.82	72.48	153.47	153.47	153.47	38.37

TABLE II-5 (Continued)ERTG MATERIAL COST

<u>TASK IV</u>	Cost in Dollars								
Phase:	<u>II</u>	<u>III</u>	<u>IV</u>	<u>V</u>	<u>V-A</u>				
Outgassing	1,000								
Vibration & Shock Test	1,800	4,000							
Misc. Tests & Material	35,000	3,000							
Endurance	2,000	3,200							
Heaters & Fixtures	45,400								
Vibration Tests (Explor.)	7,500								
Insulation Test									
(Therm. Conduct.)	50,000								
Mass Property		3,000							
Thermal Vacuum		3,600							
Characterization		1,300							
Models & Tests		2,100							
Flight RTG Testing			11,600	50,000	50,000				
S/C Power Supplies (4)			1,600						
<hr/>									
Totals	142,700	20,200	13,200	50,000	50,000				
	<u>74</u>	<u>75</u>	<u>76</u>	<u>77</u>	<u>78</u>	<u>79</u>	<u>80</u>	<u>81</u>	<u>82</u>
Totals by Fiscal									
Year in K\$	41.97	100.73	13.47	12.01	15.06	28.57	28.57	28.57	7.14

TABLE II-5 (Continued)ERTG MATERIAL COSTS

<u>TASK V</u>		Cost in Dollars				
	Phase	<u>II</u>	<u>III</u>	<u>IV</u>	<u>V</u>	<u>V-A</u>
NASA/Langley Hypersonic Tunnel		20,000				
Models		3,000				
Edgewood Sub & Trans. Tunnel		28,800				
Solid Fire Test - LASL			4,000			
Propellant			13,500			
Impact Test			9,000			
Fragment Test			2,500			
Material			1,500			
Thermal Stress - Ames			28,200			
Calibration			9,400			
Calorimeter			4,000			
T/C & Wire			450			
Sequential Tests (2)			8,000			
RTG Material			47,000			
Solid Propellant			2,000			
Liquid Prop.			500			
Blast Overpressure Test			14,000			
TNT			2,000			
Totals		51,800	146,050			
Totals by Fiscal		<u>74</u>	<u>75</u>	<u>76</u>	<u>77</u>	
Year in K\$		15.24	36.57	97.37	48.68	

TABLE II-5 (Continued)ERTG MATERIAL COSTS

<u>TASK VI</u>		Cost in Dollars				
	Phase:	<u>II</u>	<u>III</u>	<u>IV</u>	<u>V</u>	<u>V-A</u>
Power Supplies		(3)45,000	(2)30,000	(3)45,000		
PMP Material		(3)24,000	(2)16,000	(3)24,000		
Cable Sets		(3) 3,300	(2) 2,200	(3) 3,300		
Load Bank		(3) 1,500	(2) 1,000	(3) 1,500		
Fin Pads		3,000				
ETG Shipping Container		(2) 1,000				
RTG Shipping Container		6,000	(2)12,000	(4)24,000		
Handling Tools		12,000				
S/C Mounting Tool				60,000		
Miscellaneous		1,000	2,000	3,000		
Totals		96,800	123,200	100,800		

	<u>74</u>	<u>75</u>	<u>76</u>	<u>77</u>	<u>78</u>	<u>79</u>	<u>80</u>
Totals by Fiscal Year in K\$	-	-	64.53	81.55	88.32	57.60	28.80

TABLE II-6
OTHER DIRECT COSTS
 (By Phase and Fiscal Year)

	Phase:	Costs in Dollars							
		<u>II</u>	<u>III</u>	<u>IV</u>	<u>V</u>	<u>V-A</u>			
Reproduction		10,625	11,250	9,375	10,000	10,000			
Shipping		4,500	4,500	4,000	6,000	6,000			
Travel		20,250	33,700	17,500	24,500	24,500			
Computer °		88,615	178,980	60,965	57,642	57,642			
Totals		133,990	228,430	91,840	98,142	98,142			
		<u>74</u>	<u>75</u>	<u>76</u>	<u>77</u>	<u>78</u>	<u>79</u>	<u>80</u>	<u>81</u>
Totals by Fiscal									
Year in K\$		39.41	94.58	152.29	112.88	69.12	56.08	56.08	56.08
									14.02

TABLE II-7
SUBCONTRACT COSTS (DEVELOPMENT)
 (By Phase and Fiscal Year)

Phase:	Costs in Dollars				
	<u>II</u>	<u>III</u>	<u>IV</u>	<u>V</u>	<u>V-A</u>
Heat Pipe Development	93,700	10,000			
VCHP Development	211,300	20,000			
Totals	305,000	30,000			
	<u>74</u>	<u>75</u>	<u>76</u>	<u>77</u>	
Totals by Fiscal Year in K\$	126.9	178.1	15.0	15.0	

TABLE II-8
OTHER PARTICIPATING ORGANIZATIONS
 (By Fiscal Year)

GFY:	Cost in K\$								
	<u>74</u>	<u>75</u>	<u>76</u>	<u>77</u>	<u>78</u>	<u>79</u>	<u>80</u>	<u>81</u>	<u>82</u>
ORNL Capital Equipment	30	470	460	235	100	50			
ORNL Development*	104	531	563	348	162	42	12		
Heat Sources (ORNL)					295.8	591.6	591.6	591.6	98.6
Fuel (ORNL) @ \$100/Watt									
Prototype				466.3					
1st Flight & Backup					932.6				
Production					466.3	2,797.8	2,797.8	2,797.8	466.3
3M Capital Equipment	250								
3M Development	270	800	950						
T/E (3M)									
Prototype				375					
1st Flight & Backup					336				
Production					168	1,008	1,008	1,008	168
Totals	654	1,801	1,973	1,424.3	2,460.7	4,489.4	4,409.4	4,397.4	732.9

* Includes fuel capsule for the prototype heat source and the safety test program.

TABLE II-9

ERTG DEVELOPMENT PROGRAM COSTS, PHASES II THRU IV

(By Fiscal Year)

GFY:	Costs in K\$					Totals
	74	75	76	77	78	
Direct Labor	241.33	789.01	1,106.33	912.42	596.09	3,645.18
Capital Equipment Labor	-	77.47	97.85	29.63	-	204.95
Total Direct Labor	241.33	866.48	1,204.18	942.04	596.09	3,850.13
Overhead Rate (%)	142.3	139	127	135	137	-
Total Labor Cost	584.74	2,070.89	2,733.49	2,213.82	1,412.73	9,015.67
Materials	110.70	265.67	291.43	251.01	157.96	1,076.77
Other Direct Costs	39.41	94.58	152.29	112.88	55.10	454.26
Subcontract	126.90	178.10	15.00	15.00	-	335.00
Total Direct	861.75	2,609.24	3,192.21	2,592.68	1,625.79	10,881.67
G&A (%)	23.3	19	18	18.5	19	-
Total Including G&A	1,062.54	3,105.00	3,766.81	3,072.33	1,934.69	12,941.37
Fee (%)	8	8	8	8	8	-
Total Including Fee	1,147.54	3,353.40	4,068.15	3,318.12	2,089.47	13,976.68
Capital Equipment	-	402.10	250.00	100.00	-	752.1
G&A (%)	23.3	19	18	18.5	19	-
Total C.E. with G&A	-	478.50	295.00	118.50	-	892.0
Totals (Teledyne)	1,147.54	3,831.90	4,363.15	3,436.61	2,089.47	14,868.69
ORNL Capital Equip.	30.00	470.00	460.00	235.00	150.00*	1,345.00
ORNL Development	104.00	531.00	563.00	348.00	216.00	1,762.00
Heat Sources (ORNL)					197.20	197.20
Fuel (ORNL)				466.30	932.60	1,398.90
3M Capital Equipment	250.00					250.00
3M Development	270.00	800.00	950.00			2,020.00
T/E (3M)				375.00	336.00	711.00
Totals	1,801.54	5,632.9	6,336.15	4,860.91	3,921.27	22,552.77

* Includes \$50,000 ORNL Capital Equipment in GFY 79.

TABLE II-10
COST PER ERTG *

	Cost Per Generator in K\$	
	<u>Based Upon First</u> <u>10 Units (Phase V)</u>	<u>Based Upon Second</u> <u>10 Units (Phase V-A)</u>
Direct Labor		
Task I	19.368	21.061
Task II	10.637	7.472
Task III	72.986	75.813
Task IV	25.962	29.674
Task V	7.510	6.583
Task VI	.829	.900
Task VII	9.707	11.938
Totals	146.999	153.441
Direct Labor + Overhead	350.321	366.724
Materials	72.055	61.977
Other Direct Charges	9.814	9.814
Total Direct	432.190	438.515
Total (Including G&A and Fee)	555.4	563.6
Heat Sources (ORNL)	98.6	98.6
T/E (3M)	168.0	168.0
Total	822.0	830.2
Fuel @ \$100/watt(t)	466.3	466.3
Total Cost per ERTG	1288.3	1296.5
Cost/watt(e) @ EOM	3.22	3.24
Cost per ERTG with Fuel @ \$50/watt	1055.2	1063.4
Cost per ERTG with Fuel @ \$150/watt	1521.5	1529.7

* Production Rate of 1 ERTG per 2.1 months

III. COST TRADE-OFF STUDIES

In addition to the integration of cost effectiveness in all disciplines during the conceptual design phase of the ERTG, both in direct costs and manpower allocation, a number of trade-off studies were conducted to aid in cost optimization.

Some typical questions that have arisen are as follows:

1. What is the relationship between system efficiency and costs both now and in the future?
2. What is the cost advantage or disadvantage in incorporation of a thermal control system for power flattening?
3. What housing and cooling fin material is most desirable on the basis of cost?

A. SYSTEM EFFICIENCY

Table III-1 presents required fuel costs, both curium (Cm_2O_3) and plutonium (PuO_2), as a function of thermoelectric technology and hot junction temperature for a representative design of 400W(e) at EOM (5.5 years from BOL). The nominal fuel costs are based upon \$100 and \$600 per thermal watt for unencapsulated $^{244}\text{curium}$ and $^{238}\text{plutonium}$, respectively. Curium costs of \$50 and \$150 per thermal watt are also included.

The required fuel inventory at BOL, a function of the isotope's half life, for each entry in Table III-1 is obtained from the equation

$$q_{\text{BOL}} = \frac{P_o e^{\lambda t}}{\eta_{\text{T/E}} \eta_{\text{TH}}}$$

TABLE III-1

THERMOELECTRIC PERFORMANCE & FUEL REQUIREMENTS

Thermoelectric Elements	Hot Junction Temp. @ BOL (°C)	Cold Junction Temp. @ BOL (°C)	Thermal Control	T/E Efficiency (%)	BOL System Efficiency (%)	Curium Q @ BOL (Watts)	Plutonium Q @ BOL (Watts)	EOM System Efficiency (%)	Curium Fuel Cost (K\$)	PuO ₂ Fuel Cost (K\$)
TAGS/2N	550	182	Yes	7.6	7.2	7700	5784	6.4	770	3470
TAGS/2N	550	182	No	7.3	6.9	8340	6022	5.9	834	3613
Current TPM	800	175	Yes	9.6	8.6	5718	4833	8.6	572	2900
Current TPM	800	175	No	9.2	8.2	6364	5043	7.7	636	3026
Current TPM	800	200	Yes	9.1	8.2	6001	5099	8.2	600	3059
Current TPM	800	200	No	8.8	7.9	6667	5273	7.4	667	3164
Current TPM	900	200	Yes	10.3	9.3	5296	4505	9.3	530	2703
Current TPM	900	200	No	10.0	9.0	5840	4640	8.4	584	2784
Current TPM	1000	200	Yes	11.4	10.3	4781	4070	10.3	478	2442
Current TPM	1000	200	No	11.1	10.0	5256	4180	9.4	526	2508
Improved TPM	800	175	Yes	13.4	12.1	4080	3463	12.1	408	2078
Improved TPM	800	175	No	12.8	11.5	4481	3625	11.0	448	2175
Improved TPM	800	200	Yes	12.7	11.4	4292	3654	11.4	429	2192
Improved TPM	800	200	No	12.3	11.0	4717	3772	10.4	472	2263
Improved TPM	900	200	Yes	14.4	12.9	3804	3222	12.9	380	1933
Improved TPM	900	200	No	13.9	12.5	4135	3338	11.9	414	2003
Improved TPM	1000	200	Yes	15.8	14.2	3454	2937	14.2	345	1762
Improved TPM	1000	200	No	15.3	13.8	3742	3033	13.1	374	1820

- Assumptions:
1. Based on 400 watts(e) @ EOM (5.5 years from BOL).
 2. Cm₂O₃ hot pressed pellets \$100/watt(t) (nominal cost).
 3. PuO₂ hot pressed pellets \$600/watt(t).
 4. System thermal efficiency = 0.90 T/E efficiency (TPM).
System thermal efficiency - 0.95 T/E efficiency (TAGS/2N).

$$\begin{aligned}
 \text{where } P_o &= \text{power at EOM or 400 watts(e)} \\
 e^{\lambda t} &= 1.044 \text{ for plutonium} \\
 &= 1.234 \text{ for curium} \\
 &\quad \text{(Both values are based upon 5.5 years from BOL to EOM)} \\
 \eta_{TH} &= \text{system thermal efficiency} \\
 &= .90 \text{ for TPM} \\
 &= .95 \text{ for TAGS/2N} \\
 \eta_{T/E} &= \text{thermoelectric efficiency}
 \end{aligned}$$

Figure III-1 is a plot of curium fuel cost versus system efficiency as obtained from the data presented in the table. The system efficiency is taken as 90% of the thermoelectric efficiency for TPM and 95% for TAGS/2N thermoelectrics. The figure indicates a significant reduction in fuel cost as more efficient thermoelectric materials are used, and second, the projected thermoelectric technology and heat source advances allow higher hot junction temperatures. The saving in fuel cost for a plutonium fuel inventory is, of course, more significant. In either case, as advances in converter efficiency are made through research and development, fuel cost is reduced.

The data from Table III-1 also presents a comparison of required fuel inventory for systems with and without thermal control, such as a subsystem of variable conductance heat pipes (VCHP) and low temperature axially grooved heat pipes.

The second cost reduction achieved from a higher hot junction temperature and higher system efficiency is the cost of thermoelectrics. Figure III-2 provides a plot of the total cost of the required thermoelectric couples as a function of system efficiency. The improved TPM system data from Table III-2 was employed where the total cost of thermoelectrics is derived from the labor and material associated with element or couple production.

FIGURE III-1. CURIUM FUEL COST VS. SYSTEM EFFICIENCY
AT BOL

FIGURE III-2. TOTAL COST OF T/E COUPLE REQUIREMENT VS.
SYSTEM EFFICIENCY IMPROVED TPM - 400 W(e)
@ EOM

TABLE III-2Thermoelectric Requirements - Improved TPM Systems 400 Watts(e) @ EOM

Hot Junction Temperature @ BOL (°C)	Cold Junction Temperature @ BOL (°C)	System Efficiency (%)	Thermoelectric Area (in ²)	No. Thermoelectric Couples
800	175	11.5	75.1	648
800	200	11.0	84	652
900	200	12.5	60.3	552
1000	200	13.8	45.9	484
800*	175	12.1	59	543
800*	200	11.4	65.9	549
900*	200	12.9	47.9	464
1000*	200	14.2	36.5	407

*With thermal control.

B. THERMAL CONTROL SYSTEM

Due to the relatively short half-life of $^{244}\text{curium}$, approximately 20% excess thermal energy is generated at BOL. As a result of this excess heat, the power generation will not be constant but will be steadily decreasing between BOL and EOM. It therefore becomes desirable to reject the excess heat at BOL directly to space and thus maintain the thermoelectric hot junction and heat source operating temperatures at constant safe levels. This task can be accomplished by incorporating a thermal control subsystem (Reference 4) of variable conductance heat pipes. A noncondensable gas is used to block part of the condenser area and thus vary the heat pipe conductance. A portion of the heat is dissipated through the heat pipes and the remainder is conducted through the thermoelectrics. At EOM the interface between the vapor and the noncondensable gas has moved to an extent that the additional heat dissipation path (through the heat pipe) has been eliminated. At that time all of the available thermal energy passes through the converter.

Figure III-3 is a plot of curium and plutonium fuel costs as a function of hot junction temperature with and without thermal control assuming improved TPM technology. The system without thermal control requires a higher fuel inventory. A trade-off study between the cost of additional fuel and the cost associated with the incorporation of variable conductance heat pipes has also been conducted, based on the direct cost of the heat pipes required plus the development and testing necessary to integrate the heat pipes into the RTG systems. It may be noted that the necessary cost of additional fuel to compensate for the lack of a thermal control system is less at the higher hot junction temperatures. At 800°C hot junction temperature, the additional fuel cost per RTG is about \$43,000, whereas at 1000°C the cost differential is \$29,000 based on a nominal curium cost of \$100 per thermal watt. Improved TPM thermoelectric materials

FIGURE III-3. EFFECT OF THERMAL CONTROL ON FUEL COST
VS. HOT JUNCTION TEMPERATURE (ASSUMES
CURRENT TPM TECHNOLOGY)

technology is assumed. For current TPM materials and 800°C hot junction operating temperature, the additional fuel cost per RTG is about \$67,000. This is also illustrated by Figure III-3, where fuel costs are shown for systems with and without thermal control as a function of hot junction temperature for current TPM technology.

The incorporation of a thermal control subsystem of heat pipes permits a reduction of fuel inventory for an RTG. The cost saved by eliminating some fuel may or may not balance the additional cost of the thermal control. In this design evaluation the thermal control subsystem is provided by four (4) high temperature variable conductance heat pipes and fourteen (14) axially grooved low temperature Cu-H₂O heat pipes.

Figure III-4 presents the curium fuel cost reduction associated with incorporation of thermal control as a function of fuel (curium) cost per thermal watt and the cost of thermal control heat pipe development and production. The data is plotted on the basis of 10 and 20 RTG's and include the present thermoelectric technology with an 800°C hot junction temperature and future or improved TPM with 1000°C hot junction temperature.

Based upon the current thermoelectric technology and considering 10 RTG's, the break even point is \$55 per thermal watt for curium assuming thermal control. That is, if the fuel cost is above \$55, the incorporation of the thermal control appears to be economical. For current technology, the break even point is \$37 per watt and \$55 per watt for 20 and 10 RTG's, respectively. For RTG's with the improved TPM material technology and 1000°C hot junction temperature, the break even fuel costs for 10 and 20 RTG's are \$130 and \$86 per thermal watt, respectively.

This indicates that if curium is \$100 per watt, a cost saving is realized when not incorporating thermal control based upon future T/E technology and 10 RTG's. This result is further supported since the cost of a thermal control subsystem does not include the design and development dollars to integrate the thermal control with the RTG which

FIGURE III-4. COST OF ADDITIONAL CURIUM FUEL FOR
RTG'S W/O THERMAL CONTROL VS. COST
PER WATT OF FUEL

may be of considerable significance. If the selected ERTG design incorporated thermal control (at \$502,000 + for 10 RTG's), 489 thermal watts of curium can be eliminated per generator (at \$489,000 for 10 RTG's). It is also interesting to note that the curves indicate that the desirability of thermal control decreases (based strictly on cost) as other technology advances enable generator operation with higher hot junction temperature. However, this should not detract from a desire to develop thermal control systems if they are also applicable to future RTG programs as well as the ERTG.

When examining an RTG with plutonium as the fuel, the desired power flattening is relatively low at $\sim 5\%$, due to its longer half life. On the other hand, the plutonium oxide is assumed as \$600 per thermal watt, considerably more than the curium.

From Table III-1 and Figure III-4, assuming improved TPM technology, the plutonium fuel cost saving for hot junction temperatures of 800, 900, and 1000°C is \$71,000, \$70,000, and \$58,000 per RTG, respectively.

When evaluating current TPM thermoelectric materials technology where the hot junction temperature is 800°C, the plutonium cost saving for one RTG with thermal control is slightly over \$100,000 or one million dollars for 10 RTG's. A thermal control system is now more attractive.

C. OPTIMUM RADIATOR TEMPERATURE

With reference to the ERTG configuration presented, the fuel inventory can be further reduced by decreasing the radiator operating temperature. This can be readily accomplished by the addition of two fins (bringing the total to four) and doubling the number of Cu-H₂O heat pipes.

The required BOL thermal inventory would be reduced from 4663 to 4481 watts(t) or a saving of 182 watts. At \$100 per thermal watt for curium, the saving becomes \$18,200 per generator. An additional cost saving would be realized by a reduction in required thermoelectric area while maintaining the same number of couples. This saving would be approximately \$10,000.*

For reference and illustrating trends, Table III-3 provides the required fuel inventory of curium, required thermoelectric area and number of heat pipes for a representative design as a function of radiator temperature where the hot junction temperature at BOL is 800°C. The data is also based on future TPM T/E technology. As radiator temperatures are reduced, both fuel inventory and T/E area requirements are reduced, whereas the number of heat pipes is increased. However, the savings obtained from reduced fuel and T/E area more than compensate for the additional cost associated with more heat pipes. Figure III-5 provides a plot of curium fuel cost and T/E area as a function of radiator temperature at BOL.

The cost disadvantages are based upon the need for more heat pipes (\$13,400) and additional fin material and fabrication (\$10,000). The total saving from addition of the above four entries becomes \$4,800. However, not all of this potential saving may also be realized because the heat pipe-fin bonding development and production costs would also increase. The additional heat pipes added to reduce radiator temperature necessitate 90° bends and provide greater bonding complexity. Therefore, if any saving would be realized from this approach, it would be a function of plutonium fuel costs and not curium.

*This cost is derived from the assumption that approximately 50% of the T/E couple cost is for materials. Therefore, if the number of couples is about constant for comparing two generators (such as shown per Table III-3) the cost differential is only dependent upon the T/E material volume ratio.

FIGURE III-5. CURIUM FUEL COST AND T/E AREA
VS. RADIATOR TEMP. (FUTURE TPM
TECHNOLOGY)

TABLE III-3
REQUIREMENTS OF FUEL INVENTORY, NUMBER HEAT PIPES
AND T/E AREA AS A FUNCTION OF RADIATOR TEMPERATURE

No. Fins	Radiator Temp. (°F)	EOM T/E Efficiency (%)	EOM System Efficiency (%)	Q @ BOL (W(t))	T/E Area(in ²)	No. of Cu/H ₂ O Heat Pipes	No. Couples
4	240	12.80	11.01	4481	64	76	630
4	270	12.45	10.81	4570	71	80	633
2	300	12.05	10.59	4663	76	40	638
2	330	11.59	10.35	4772	83	36	644

Assumptions: Hot Junction Temperature @ BOL = 800°C

Future TPM Technology

No Thermal Control

400 Watts (e) at 5.5 years

Element Length = 0.3"

Fuel: Curium 244

The incorporation of additional fins and heat pipes provides other disadvantages. The increase in weight would be about 8-12 pounds and most important, the operation of the thermoelectrics below 150°C (280°F radiator temperature at BOL) has not been verified as acceptable at this time.

D. ERTG HOUSING AND FIN MATERIAL

Both a magnesium-thorium alloy (HM21A or equivalent) and an aluminum alloy (6061-T6) were the prime candidate materials for the housing and fin structure of the RTG. The former has been extensively used in the past for RTG housings and immediately suggests a light weight or minimum weight structure. This is true for most applications; however, an aluminum structure can be designed such that the increase in weight is relatively insignificant and the advantages obtained from applying aluminum are very significant. One of these features is simply the cost per pound of wrought material. The design of the housing requires that it be machined from plate stock rather than assembled of welded sheet material. The jigs and fixtures required for welding the numerous fins and stiffeners would not provide any process cost saving and the warping of surfaces would be significant. Hence, the initial volume of material is large per RTG, and \$1.25 per pound and \$27.00 per pound represent the cost of aluminum and magnesium, respectively.

The additional weight from the use of aluminum for the reference design is only about five pounds. This increase is minimal, since the strength and rigidity of aluminum are much higher than the corresponding properties of the magnesium alloy and thinner sections could be incorporated.

Assuming 6061-T6, the basic material cost per RTG is about \$550. However, assuming HM21A, the material cost per RTG is \$7,400. Therefore, the direct material

cost saving becomes \$68,500 for 10 generators and \$137,000 for 20 generators. These values are somewhat conservative since additional savings are realized when considering ETG's and additional test hardware.

Although one cannot assign an accurate dollar value, a considerable cost saving will be realized in the development of a dissimilar metal joint for a hermetic seal. The coefficient of thermal expansion of aluminum is less than that of magnesium alloys and the existing technology base for aluminum/dissimilar metals is very good and adaptable to both electrical connector and heat source seals.

Aluminum alloys, especially 6061, are always available in large volumes. This is not the case for magnesium-thorium alloys, where the number of normally scheduled mill runs per year does not exceed two. Additional advantages of aluminum must include easier and more reliable welds, a greater technical data base, and the chloride inclusion problem associated with magnesium-thorium is nonexistent in aluminum.

There is also a potential saving in the machining time for aluminum. A forging or extruded section might replace the plate stock normally employed for magnesium-thorium. Therefore, a 30-50% saving may be realized in machining.

E. NEUTRON SHIELD

The initial material selection for the neutron shield was cast lithium hydride. However, with equivalent capability, a minimal weight gain and a large cost differential, a polyethylene shield is proposed as a substitute.

Informal price quotations for the lithium hydride included \$35,000 to reactivate the subcontractor's facility, \$20,000 for the first test unit and \$15,000 per unit for orders of ten or more. Therefore, for ten production units plus the prototype and Phase IV flight unit, the total cost would be \$220,000. Including an additional ten production units, the total cost would be \$370,000.

The polyethylene shield could be either molded or fabricated from plate stock. The polyethylene will be canned in a reinforced aluminum shell structure of sheet and extruded stock. This approach will result in a material cost per unit of approximately \$450. Therefore, for a production of 10 and 20 flight units (12 and 22 total) the material cost becomes \$5,400 and \$9,900, respectively. The burdened labor cost per unit (design + manufacturing + quality control) is approximately \$800. Therefore, total labor is \$9,600 and \$17,600 for production runs of 10 and 20 units, respectively.

The resulting cost saving is delineated in Table III-4.

F. SUMMARY

Numerous curves for thermoelectric performance, heat rejection temperatures, thermal inventory, etc., were presented in this report and applied in the optimization of the selected design. Major cost savings were also made in the selection of housing, fin and neutron shield materials.

Cost effectiveness was applied to every aspect of the program, including material selection, test facility and planning, fabrication methods, and manpower allocations. A partial list of items contributing to lower costs is presented below.

1. Dual fuel capability without requiring generator modification.
2. Extensive use of aluminum - low cost and ease of fabrication.
3. Straight heat pipes - minimized tooling and bonding complexities.
4. Only two cooling fins - four fins or more would require curved or bent heat pipes and provide higher weight.
5. Fueling port mechanically sealed - allows for substitution or replacement of heaters or heat source with minimal effort and no rework.
6. Housing and heat sink bars with no curved surfaces - minimizes machining and waste material costs.

7. Use of selenide T/E material for increased conversion efficiency.
8. Min-K insulation rather than multi-foil insulation.
9. Minimum application of full scale generators during development with emphasis placed on testing "1/5 stack" modules and smaller modules.
10. "Standard" cold end hardware. Use of proven technology of pistons and springs to provide desired contact load.
11. Modularity approach to minimize cost of adapting design to other power level requirements. Modular approach includes matched thermoelectric modules, heat sources, and heat pipes. The concept provides power variations in 80 watt increments (scalability) with only minimal redesign of the housing required.
12. Structural members optimized for maximum rigidity and minimum weight.

TABLE III-4
COST SAVINGS FOR NEUTRON SHIELDING

	<u>10 RTG's</u>	
	<u>Lithium Hydride</u>	<u>Polyethylene</u>
Subcontract	\$220,000	-
Materials	-	\$ 5400
Labor	-	9600
Cost Saving		\$ 205,000

	<u>20 RTG's</u>	
Subcontract	\$370,000	-
Materials	-	\$ 9900
Labor	-	17,600
Cost Saving		\$ 342,500

IV. REFERENCES

1. "The Availability and Cost of Curium-244 from Power Reactor Fuel Reprocessing Wastes," by Brown, Lamb and Albertson, 8th Intersociety Energy Conversion Engineering Conference, Philadelphia, Pa., August 1973.
2. Letter from R. T. Carpenter (AEC/SNS) to W. E. Osmeyer (Isotopes), dated August 10, 1973.
3. Letter from R. T. Carpenter (AEC/SNS) to W. E. Osmeyer (Isotopes), dated September 24, 1973.
4. Dynatherm Report DTM-73-14, "Economic RTG Heat Pipe Study - Development Plan," dated September 13, 1973.

APPENDIX AHEAT PIPE COST DATA * (DYNATHERM)

	Standard Cu-H ₂ O HP's	Axial Grooved Low Temp. HP's **	High Temp. VCHP's	Totals
<u>A. Development (\$K)</u>				
Configuration Definition	9.6	-	15.3	24.9
Development	34.3	16.6	79.2	130.1
Design & Qualification	59.8	20.4	99.8	180.0
Totals	103.7	37.0	194.3	335.0
<u>B. Production Costs (Unit Price, \$)</u>				
For 1 RTG	461	350	2950	
For 10 RTG's	391	299	2495	
For 20 RTG's	371	286	2379	
Total Thermal Control Costs (\$K) ***				
\$248,000 for 1 RTG				
\$373,000 for 10 RTG's				
\$501,700 for 20 RTG's				

* Costs do not include RTG integration development and design.

** Some development effort obtained from the standard Cu-H₂O heat pipes.

*** Based upon 14 axial grooved and 4 VCHP's per RTG.

FIGURE A-1. COST OF Cu-H₂O HEAT PIPES

APPENDIX BFUEL ENCAPSULATION COSTS (ORNL)

The various costs delineated below include the materials, fuel capsule production, development and testing support to be provided by the fueling agency, Oak Ridge National Laboratory.

Heat Source Production (less fuel):

Prototype Unit	\$145,000	(Ref. B-1)
Flight Unit	98,600	

These estimates include all materials and fabrication, except as noted below, capsule fueling operations, inspection, acceptance testing, heat source assembly, and generator loading. The costs do not include final machining of the formed liners, strength member material and fabrication, vents, capsule supports, and heat shields, nor the Pt-3008 for the prototype unit. The costs for the latter items are reflected in the Teledyne-Isotopes estimates per Chapter II of this report.

Capsule liner piece parts of platinum 3008 included within the estimates are based upon current market prices for platinum and rhodium of \$150 and \$220 per troy ounce, respectively (Reference B-2).

Development

Table B-1 presents the estimated costs per fiscal year for the development program. Note that test capsule fabrication, liner material, and the required fuel simulant for fifty (50) units are included in this tabulation.

Capital Equipment

The capital equipment cost per fiscal year in support of heat source production is presented in Table B-2.

TABLE B-1
 ORNL DEVELOPMENT PROGRAM IN SUPPORT OF TELEDYNE
 ISOTOPES ERTG PROGRAM - OPERATING
 COST BREAKDOWN BY FISCAL YEAR (REF. B3)

<u>Task</u>	<u>Cost (Thousands of Dollars)</u>						
	<u>FY 74</u>	<u>FY 75</u>	<u>FY 76</u>	<u>FY 77</u>	<u>FY 78</u>	<u>FY 79</u>	<u>FY 80</u>
Contractor Liaison	5	13	13	12	12	12	12
Coating Procedures	-	52	92	-	-	-	-
Non Test	6	86	106	26	-	-	-
Welding Procedures ¹	-	116	135	15	-	-	-
Fabrication Development	80	160	-	-	-	-	-
Physical Metallurgy Support	-	20	20	10	-	-	-
Shielding Design Studies	5	15	30	-	-	-	-
Vent Evaluation	3	20	8	-	-	-	-
Source Criticality Studies	2	6	6	-	-	-	-
Fuel Simulants	3	10	5	-	-	-	-
Loading and Handling Procedures Tools and Equipment	-	33	18	15	-	-	-
Prototype Test ²	-	-	50	230	120	30	-
Flight Safety Tests Vibration Test	-	-	-	-	30	-	-
Capsule Fabrication ³	-	-	80	40	-	-	-
Summary	104	531	563	348	162	42	12
Total Cost (K\$)	1762						

¹Includes special materials for weld development.

²Does not include the cost of the fuel.

³Includes material cost for 50 units.

TABLE B-2
 ORNL DEVELOPMENT PROGRAM IN SUPPORT OF TELEDYNE
 ISOTOPES ERTG PROGRAM - CAPITAL EQUIPMENT

<u>Task</u>	<u>Cost (Thousands of Dollars)</u>					
	<u>FY 74</u>	<u>FY 75</u>	<u>FY 76</u>	<u>FY 77</u>	<u>FY 78</u>	<u>FY 79</u>
Coating Procedure	-	50	50			
Nondestructive Test	-	80	120	40		
Welding Procedures	-	40	60	20	-	-
Fabrication Development	-	220	-	-	-	-
Physical Metallurgy Support	20	-	-	-	-	-
Vent Evaluation	-	30	20	-	-	-
Loading and Handling Procedures Tools, and Equipment			60			
Prototype Test			100	50	50	
Vibration Test				75		
Miscellaneous	<u>10</u>	<u>50</u>	<u>50</u>	<u>50</u>	<u>50</u>	<u>50</u>
Summary	30	470	460	235	100	50
Total Cost (K\$)	1345					

REFERENCES

- B-1 Letter from E. Lamb (ORNL) to W. Osmeyer (Isotopes), dated September 18, 1973 .
- B-2 Letter from K. Haff (ORNL) to W. Osmeyer (Isotopes), dated September 27, 1973 .
- B-3 Letter from K. Haff (ORNL) to W. Osmeyer (Isotopes), dated October 11, 1973 and revised by telecon November 6, 1973.

APPENDIX CTHERMOELECTRIC COSTS - 3M CORPORATION

Continuous AEC Technology Program Support	\$600 K per year
Component Demonstration Program & Development (Period of ~ 18 months)	
TPM-217 Couple Technology	\$175K
Test Fixtures (Mfg. & Materials)	
10 - 20 couple modules	\$ 50K
20 - 10 couple modules	\$200K
10 - 66 couple modules	\$550K
Assembly	\$120K
Testing and Analysis	\$175K
Capital Equipment	\$250K
One ETG + One RTG (Hardware, Assembly, & Tooling)	\$750K
One additional ETG	\$375K
Production Units \$420/watt X 400	\$168K per unit

REFERENCES

- C-1 Letter from E. F. Hampl (3M) to F. Russo (Isotopes), "Cost Estimate for ERTG Program," 2331-0367, dated October 22, 1973.